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Is it only CO_2 that matters? A life cycle perspective on shallow geothermal systems

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ABSTRACT

Shallow geothermal systems such as open and closed geothermal heat pump (GHP) systems are considered to be an efficient and renewable energy technology for cooling and heating of buildings and other facilities. The numbers of installed ground source heat pump (GSHP) systems, for example, is continuously increasing worldwide. The objective of the current study is not only to discuss the net energy consumption and greenhouse gas (GHG) emissions or savings by GHP operation, but also to fully examine environmental burdens and benefits related to applications of such shallow geothermal systems by employing a state-of-the-art life cycle assessment (LCA). The latter enables us to assess the entire energy flows and resources use for any product or service that is involved in the life cycle of such a technology. The applied life cycle impact assessment methodology (ReCiPe 2008) shows the relative contributions of resources depletion (34%), human health (43%) and ecosystem quality (23%) of such GSHP systems to the overall environmental damage. Climate change, as one impact category among 18 others, contributes 55.4% to the total environmental impacts. The life cycle impact assessment also demonstrates that the supplied electricity for the operation of the heat pump is the primary contributor to the environmental impact of GSHP systems, followed by the heat pump refrigerant, production of the heat pump, transport, heat carrier liquid, borehole and borehole heat exchanger (BHE). GHG emissions related to the use of such GSHP systems are carefully reviewed; an average of 63 t CO_2 equivalent emissions is calculated for a life cycle of 20 years using the Continental European electricity mix with 0.599 kg CO_2 eq/kWh. However, resulting CO_2 eq savings for Europe, which are between −31% and 88% in comparison to conventional heating systems such as oil fired boilers and gas furnaces, largely depend on the primary resource of the supplied electricity for the heat pump, the climatic conditions and the inclusion of passive cooling capabilities. Factors such as degradation of coefficient of performance, as well as total leakage of the heat carrier fluid into the soil and aquifer are also carefully assessed, but show only minor environmental impacts.

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1. Introduction

Geothermal heat pumps (GHPs) have evolved as an attractive technology for space heating and cooling. It is predicted that worldwide use of such systems will exponentially increase in the next decades [1,2]. GHPs utilize the underground as a free geothermal energy reservoir or storage medium (e.g. aquifer thermal energy storage) and thus can be applied nearly everywhere, even in areas of low geothermal gradient. There are mainly two types of GHPs. In open systems such as groundwater heat pump (GWHP) systems, wells are installed and groundwater is used directly as heat carrier. However, much more common are closed systems (ground source heat pump, GSHP systems), where boreholes are equipped with pipes that act as borehole heat exchangers (BHEs). Energy transfer between the BHEs and the ground is established by circulating a synthetic heat carrier fluid. Before putting a GHP in operation, boreholes have to be drilled, extraction and injection wells or BHEs have to be installed in the ground. Furthermore, these devices have to be connected to the heat pump in the building. Commonly such boreholes reach shallow depths (<400 m). Deeper geothermal technologies such as enhanced geothermal systems (EGS) are more sizeable and are mainly installed for the generation of electricity (e.g. [3]).

As a low enthalpy system, a GHP continuously consumes primary energy for secondary energy production. The temperature of the heat carrier fluid is low grade and cannot reach values higher than the shallow ground. The heat pump extracts energy from the carrier fluid by compressing and evaporating a refrigerant. This is a critical step that costs energy, in most cases electrical power from the grid. The consumption of energy rises with the absolute increase a heat pump has to achieve from carrier fluid temperature to the desired space temperature. For quantifying the energy efficiency of GHPs, a seasonal performance factor (SPF) and a coefficient of performance (COP), which is the ratio between the the amount of heat delivered to a hot reservoir and the heat pump compressor's dissipated work, are commonly used. Typical reported values for COP range between 3 and 5 for temperature differences between 0 and 35 °C [4,5].

As indicated by the COP, geothermal heat can hardly be considered as fully renewable. In fact, this is also true for mining of alternative energy resources that are considered environmentally benign (e.g. [6]). However, for GHPs energy is consumed mainly during operation, in contrast to energy generation from solar or wind where manufacturing of equipment is most relevant [7,8]. For GHP systems, net greenhouse gases (GHG) emissions depend on the type of primary energy source for power supply, its demand and the relative amount of geothermal energy developed. Obviously, the environmental impacts of such different technologies are ideally compared by examining their entire life cycle instead of picking out particular stages (e.g. construction and disposal). This may be intricate, especially if distinct types of emissions are produced at different points in time, with their specific effects and if they are calculated in variable units.

In this study, we focus not only on the net energy consumption and greenhouse gas (GHG) emissions or savings by GHP operation, but adopt a life cycle perspective to fully examine the environmental burdens and benefits related to applications of shallow geothermal systems. A state-of-the-art life cycle assessment (LCA) framework is set up. This standardized evaluation method enables us to trace the entire energy flows and resources use for any product or service. All stages in a product's life, from extraction of natural resources and processing of raw materials, through production, distribution, use, to the final disposal, are taken into account. In such a cradle-to-grave approach, all up- and downstream inputs and outputs along all the phases of the life cycle are analyzed and evaluated. Until now, most studies exclusively rate environmental impact of GHPs only on its potential to save energy and hence greenhouse gas emissions [1,9–11]. Existing LCA concepts not only focus on issues related to energy flows and global warming, but also examine potential adverse effects on other environmental safeguard subjects such as depletion of ozone layer or land use [7,12,13]. This is also considered in this study and the relevance of these different impact categories for GHPs is elaborated.

In the following, a selective review of projects and studies on low-enthalpy geothermal heating systems is presented. Special focus is set on those that discuss the environmental performance or that define environmental indicators for the systems design. A range of different environmentally relevant factors and consequences are elaborated and then embedded into a LCA framework. We ask what role other environmental impact categories, besides climate change, play, and if they are appropriately reflected. This is answered by contrasting experience from previous studies with the results from LCA application to a typical GSHP system. The GSHP system supplies a single family house with a heating and cooling demand of 10 kW and 5 kW, and is investigated by several representative scenarios.

2. Related work

2.1. Carbon dioxide as proxy for environmental effect

In numerous studies on GHP applications, generated or saved GHG emissions are regarded as surrogate or proxy for environmental threat or benefit. For example, Lo Russo et al. [14] calculated significant potential savings in energy use and CO_2 emissions as a main argument for using low-enthalpy geothermal technologies for space heating and air conditioning in the region of Piemont, Italy. Blum et al. [9] studied the total CO_2 savings of vertical GSHP systems in a state in South Germany. They concluded that for the studied state the minimum resulting CO_2 savings for one installed GSHP unit (using a COP of 4) is about 1800 kg per year using the average CO_2 emission of the German electricity mix.

Akella et al. [15] identified social, economic and environmental impacts related to renewable energy systems in India, but exclusively ranked different technological options with respect to associated GHG emissions. Yasukawa et al. [16] provide an insight into the long-term prospects of the use of geothermal energy and their environmental effects in Japan. Three scenarios are presented to delineate possible increases of geothermal energy

Table 1
Selected case studies on buildings and facilities with low-enthalpy and shallow geothermal heat pump systems. Data are taken from monitored case studies, from planned projects (feasibility studies), and from hypothetical systems (synthetic studies).

Type of building/facility	Study case	Status	Type of geothermal heat pump (GHP) system	Installed capacity/ annual heat production	Annual CO_2 savings	Remarks	Reference
Academy	NW England	Feasibility study	GSHP	1.2 GWh/year for heating, 333 MWh/year for cooling	108 t; compared with fossil fuel based heating, 20 years	Conventional plant includes gas boilers and electric chillers; only energy consumption for heat pump	[62]
District, 1 km^2 region, high-rise buildings	Nishi (West)-Shinjuku area of Tokyo, Japan	Feasibility study	GSHP with 43,200 BHEs, COP (heating) = 4.8, COP (cooling) = 4.9	230 GWh/year for heating, 330 GWh/year for cooling	39,519 t, 54% reduction compared to ASHP system in operation; 20 years	GHG emissions from transportation of the cooling tower, materials for the underground heat exchanger, and the digging loads and transportation loads incurred when the GSHP system is installed to replace air source cooling system	[17]
Residence	Germany	Synthetic study	Combined horizontal and vertical open system, low temperature groundwater	40 kW capacity, 1800 h/year full load hours	43% reduction compared to fossil fuel (723–817 GJ/TJ energy consumption, 50–56 t/TJ CO_2 eq.)	LCA, without interpretation, finite energy resource consumption, additional anthropogenic greenhouse effect, acidification of lakes and rivers, human- and ecotoxicity	[8]
District, small residential suburb	Germany	Synthetic study	“deep wells”, heat pump only for provision of base load, peak load based on fossil fuel energy	3 MW capacity, 1800 h/year full load hours	53% reduction compared to fossil fuel (744 GJ/TJ energy consumption, 50–50 t/TJ CO_2 eq.)		[8]
District, village of 200 houses	Sanmartin, Romania	Feasibility study	GWHP, 100 l/s, ca. 40 °C groundwater in 80–175 m depth, heating by 20 °C decrease	4 MW capacity (needed)	6113 t, compared to solid fuel (wood) combustion		[18]
Residence, single family	West Grimstead, UK	In operation (since 1998)	GSHP, single BHE, 200 m depth, COP = 3.2 (heating period, continuous running of distribution pump)	4 kW capacity; 14 MWh/year	2.6 t (58% reduction compared to electric), 3.6 t, (50%, oil-fired boiler), 0.6 t, (15%, gas-fired boiler); lifetime ≧20 years	Only absolute heat gain/ consumption and/or total energy production	[63]
Office building	Lyon, France	In operation (since 1997)	GSHP, COP (heating) = 4.75, COP (cooling) = 3.75	1.2 MW capacity; 2.1 GWh/year	262 t, 71% reduction compared to gas fired boiler and chiller	Incl. refrigerant leakage	[63]
School building	Charleston, school building, UK	In operation (since 1999)	GSHP, 10 BHEs of 70 m		60–70% compared to the old system (direct electric heating)	Only absolute heat gain/ consumption and/or total energy production	[63]
Residence, single family	Central Pennsylvania, USA	In operation (since 2004)	GSHP, 4 BHEs of 45 m, COP = 5.3	12.3 kW capacity cooling, 8.7 kW capacity heating	6.1 t (62% reduction compared to hybrid system of heating oil and electrical power), 7.8 t (80%, all-electric heating)	Only absolute heat gain/ consumption and/or total energy production	[64]
Large building	UK	Synthetic study	GSHP, high-efficiency boiler; COP = 3.8; heating only	n.a.	49% reduction compared with natural gas heating	0.11 kg CO_2 per delivered kWh from UK electricity grid	[65]
Large building	UK	Synthetic study	GSHP, high-efficiency boiler; COP = 4.8; heating and cooling	n.a.	60% reduction compared with natural gas heating (during heating season)		[65]
Large building	UK	Synthetic study	GSHP, cooling-only heat pump with a COP of 4.2	n.a.	40% reduction compared to using an air-conditioner with COP of 2.5 (cooling only)		[65]

Office building	Ghent, Belgium	Feasibility study	GSHP with 90 BHEs of 125 m; combined with gas fired boilers and compression chillers	500 kW heating, 350 kW cooling; 900 MWh/year heating; 281 MWh/year cooling (only GSHP)	128 t (31% reduction compared to chiller and oil-fired boiler)	Simulation with annually decreasing efficiency; only operation	[66]
Office building	Winnebago Reservation, Nebraska, USA	Feasibility study	GSHP	72 kWh/year heating; 140 kWh/year cooling	15 t (compared to rooftop units with gas heat)	Majority of electricity supplied by the utility is generated by coal fired power plants; CO_2 equivalents CH_4, NO_x, etc.	[67]
Office building	Motor Tax Office, Kerry, Ireland	In operation (since 1999)	Horizontal GSHP, 5100 m length	130 kW capacity	52% (compared to BRESCO type 3 office building)	Only absolute heat gain/ consumption and/or total energy production	[68]
Office building	Landfill Site office, Kinsale Road, Cork, Ireland	In operation (since 2000)	Horizontal GSHP, 2400 m length	28 kW capacity	30% (compared to natural gas fired boiler)	Only absolute heat gain/ consumption and/or total energy production	[68]

uses in the future (2020 and 2050). The environmental effects of the most optimistic scenario are only expressed with respect to savings in fossil fuel (energy amounts equivalent to 80.1×10^9 l of oil), and the respective reduction of emitted CO_2 (61.6×10^6 t in total).

Table 1 offers insight into the findings from a variety of case studies. The calculated GHG emission savings of GHP vary and depend on (hydro)geological conditions, technology and technological design, (time-dependent) heating/cooling requirement, CO_2 intensity of primary energy for running heat pump, as well as the available alternative heating/cooling system. For example, Genchi et al. [17] examined the life cycle of alternative geothermal district heating systems for high-rise buildings in Tokyo (Nishi-Shinjuku). The potential of replacing an air source heat pump (ASHP) system with a GSHP system is judged by the expected CO_2 savings and by the payback time in CO_2 emissions. In this case, environmental payback time would be 1.7 years if the GSHP system is implemented, with more than 50% CO_2 saving potential considering the full life cycle.

In their study on the village Sanmartin in Romania, Blaga et al. [18] discuss the environmental and economic benefits of replacing the mainly wood-based single-house heating systems with a shallow geothermal district heating system. They identify not only significant advantages with respect to CO_2 savings from operating open systems (GWHPs), but also emphasize the decrease of other combustion and gas ash emissions, as well as residual heat loss from releasing combustion gases to the air. By operating heat exchangers based on plates overall environmental impacts are predicted to be close to zero. For a planned district heating system in Greece, Agioutantis and Bekas [19] calculated annual fossil fuel savings of 4.7 GWh and annual CO_2 savings of 1516 t by developing a 50–70 °C geothermal reservoir.

Fridleifsson et al. [1] estimated about 33–50% savings in CO_2 emissions by using GSHP systems instead of fossil fuel fired boilers. This is similar to the studies by Blum et al. [9], who estimated CO_2 savings of 35% or 72% depending on the supplied energy for the heat pumps and the efficiency of installation. The case studies listed in Table 1 exhibit savings between 15% and >80% when compared to conventional, mostly fossil fuel based heating systems. Fridleifsson et al. [1] state that using hydropower, for example, for driving the heat pumps means no CO_2 emissions at all. In more detail, Hanova and Dowlatabadi [20] presented a synthetic study on the trade-offs between CO_2-intensity of primary energy source, a technology's heating load and ranges of COP. Calculations are based on the fixed figures of conventional fuel CO_2 emissions versus those from heat pumps: natural gas heating is associated with 51 kg CO_2 eq/GJ, while heating oil produces 73 kg CO_2 eq/GJ. However, their findings are solely based on the power consumption for the heat pump instead of considering the whole life cycle of the GSHP systems, which is needed for a comprehensive environmental assessment. This is similar to the study by O'Connell and Cassidy (2003), who reflect the situation of large scale GHP installations such as vertical and horizontal GSHP and GWHP systems in Ireland. CO_2 emission savings by using horizontal GSHP systems are estimated to be 30% in comparison to natural gas heating, 45% to oil-fired boilers and even 100% when utilizing a renewable energy resource for electricity. The potential for geothermal heating in Ireland, a country with only few installations at the moment, is thought to be enormous. By primary energy savings for residential and tertiary sectors of about 2400 TWh/year or 617,000 t CO_2/year could be saved.

Jenkins et al. [21] examined the potential CO_2 savings of closed horizontal-loop GSHP systems in the UK. They highlight the role of the output temperature of the heating system. Predicted savings when compared against a gas boiler are almost 40% for 35 °C (COP = 4.4) output flow temperature but just over 4% for 55 °C

(COP = 2.8). Given ranges of carbon savings in this study are between 0% (and below) and 80%. In their study, they also discuss possible feedbacks of rising market shares of GHPs on the electricity grid. A scenario is discussed where GHP installations are mainly run during daytime and thus accentuate overall daytime peaks in power demand. In this scenario, higher electrical demand is mainly compensated by fossil-fuel based power plants that can be modulated. Accordingly, one could argue that GHPs have generally therefore a higher ratio of CO_2 intensive electricity from the grid. Thus, electricity generation would need to react to rising numbers of GHP by more modulated power plants and ultimately this feedback would mitigate their CO_2 saving potential. These findings are debatable, since the need for more modulation does not inevitably result in more CO_2 intensive electricity generation. For example, modulation of coal-fired plants is difficult, probably more difficult than modulation of GHPs.

Rybach [11] emphasizes that the major potential of GHPs is avoidance of additional GHG emissions rather than reduction. Strictly speaking, reduction is only possible when GHG systems replace existing heating systems, and predictions of GHG savings mostly assume installations in new buildings. Based on the findings of a study of the European Heat Pump Association [22], Rybach [11] identifies an enormous GHG emission avoidance potential of heat pumps in Europe. Annual increase rates of 5.4 million heat pumps are expected, and based on calculations with the average European electrical energy mix 230 million t CO_2/year could be avoided. Such savings would represent 20% of the European GHG emission savings goal.

2.2. Concepts for consideration of further environmental effects

Environmental burdens of GHPs are not only caused by GHG emissions, which are considered most relevant for global climate change. There exist threats to other environmental entities such as the ozone layer, which can be depleted, or natural water resources that are impacted [23–25]. Vera and Langlois [26] provide an overview of a range of sustainability indicators to assess energy production and use patterns in general on the national scale. For comparison of alternative power generation technologies, Evans et al. [27] also compiled apposite indicators. These include economic efficiency of energy conversion and related social impacts that occur during the life cycle of energy generation technologies. Interestingly, their general analysis of solar, wind and hydro power revealed geothermal energy for the production of electricity as the least environmentally friendly choice. However, it is clear that such a global assessment is critical for geographically variable criteria such as land, water and resource availability. Pehnt [7] presented a dynamic LCA approach for renewable energy technologies that considered time-dependent boundary conditions for predicting the environmental effects of using renewables in the future. A dialectic discussion is presented that avoids universal ranking but is based on specific case-studies. Again, focus is set on electricity generation. The comprehensive LCA study by the World Energy Council [28] on alternative energy systems includes electricity production, space heating and transportation. However, among the different technologies, the use of geothermal energy for space heating was not examined. The focus by Huenges and Frick [29] is on enhanced geothermal system (EGS) plants. They compare the long-term CO_2 savings potential as well as costs of such deep geothermal systems in comparison to CO_2 sequestration.

Kaltschmitt [8] suggested a LCA based on the framework by Heijungs et al. [30] for environmental examination of a range of different geothermal heating technologies. Among these, the open GHP system variant, GWHPs, was also analyzed. In line with LCA standards, not only expected CO_2 emission was calculated, but also atmospheric emissions in CO_2, SO_2, NO_x equivalents, and non-renewable energy consumption. Unfortunately, the underlying assumptions, system boundaries and data sources are only incompletely reported. Furthermore, an interpretation with respect to their environmental impact is missing. The major conclusion of the study is that due to the dominating GHG emissions, the type of primary energy resource used for GWHP operation is of major importance and the net share fossil fuel governs the system's environmental profitability.

For a fixed primary energy mix that relies on fossil fuels, GHG emissions correlate with energy efficiency. The more energy is consumed for a certain heating effort, the more GHG are emitted. However, in many cases this relationship is not trivial, and one may be interested in net energy consumption or production. For a quantitative analysis of technologies' energy contents and losses, the concept of exergy is frequently used. It is based on the first law of thermodynamics and established in the field of energy-intensive industries. Koroneos et al. [10] employed an exergy based evaluation to compare electrical power generation by common renewable energy sources such as solar, wind and geothermal. Hepbasli [31] presents a comprehensive overview of further applications and available methodologies. Calm [34] discusses the cumulative exergy extraction from the environment as a suitable concept in LCA. For energy resource accounting, the most established indicator in LCA is still summing up the energy in- and outputs in a natural resource consumption indicator [33].

An environmentally crucial factor that is frequently ignored when weighing the green aspects of GHPs is the use of refrigerants in the heat pump. A broad range of different refrigerants are compared in a previous study [34]; and in two other studies their use in GHP systems is discussed [35,36]. Among the commonly used substances are hydrofluorocarbons (HVCs), which represent GHG with a global warming potential that is much higher than that of CO_2 (by a factor of typically 1400–1900) [37]. Atmospheric emissions occur by leakage during operation and when dismantling the heat pump, and thus have to be taken into account for a full environmental assessment [38]. Meanwhile, alternatives to standard refrigerants are considered such as hydrocarbons and ammonia, although at the expense of a lower COP and thus higher energy consumption. Furthermore, in a study by the European Heat Pump Association [4] the improvement of HVC control by setting minimum regulative standards for inspection and recovery is discussed.

Another refrigerant that has to be taken into account for closed GSHP systems is the heat carrier liquid circulating in the borehole heat exchanger. Favorable properties are a high specific heat capacity, high heat transfer coefficient and low viscosity. They should guarantee a long lifetime, with low reactivity, risk of corrosion and biofouling. Most common are aqueous solutions of glycol and ethyl alcohol. Klotzbücher et al. [39] studied the biodegradability and potential risk for groundwater pollutant of such liquids. They found out that ethylene and propylene glycol are readily biodegradable under both oxic and anoxic conditions. Thus, no long-term groundwater contamination by these glycols is expected. However, other critical and toxic chemical additives are commonly used in such BHE fluids such as corrosion inhibitors or biocides (e.g. borates and sodium nitrite) [40]. Klotzbücher et al. [39] state that small amounts of additives can pose specific threats while also acting as inhibitor for in situ glycol degradation. Their study also showed that these additives can inhibit biodegradation of commercial antifreeze compounds and therefore may cause adverse effects on subsurface microbial communities and on groundwater quality in the case of leakage. However, no detailed information on the chemical identity of such specific additives is currently available.

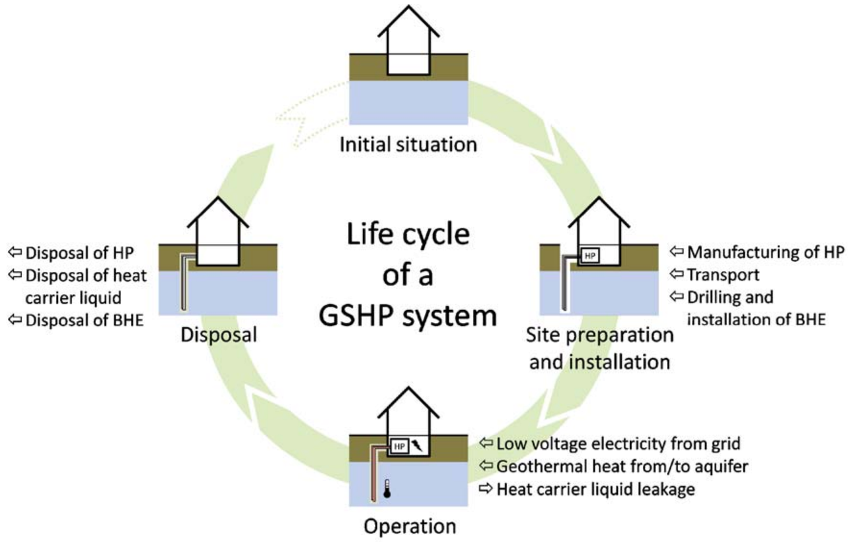


Fig. 1. Different life stages of a ground source heat pump (GSHP) system and the main flows of unit processes contributing to the life cycle.

So far, to our knowledge no comprehensive analysis is presented on shallow geothermal systems that contrasts the role of the individual technological elements, including well or BHE, heat pump, different types of refrigerants and power supply. Considering the most common technology, the closed GSHP systems that are literally isolated from the environment, there is consensus that focus should be set on minimizing the energy use for operating the heat pump. In the following, a complete LCA for GSHP systems is presented that examines the environmental effects with respect to 18 impact categories. As a representative study case, a central European one-family house with a heating and cooling demand of 10 kW and 5 kW respectively is considered. Several scenarios are used to obtain insight into the relative importance of technology- and country-specific factors for different environmental impact categories.

3. LCA methodology

The technical guidelines for the LCA methodology have been standardized by the International Organization for Standardization (ISO) [41,42]. It is described as a procedure with four phases: (1) the goal and scope definition, in which the studied product and purpose of the study are defined; (2) the inventory analysis, in which data of the unit processes of the product system are collected, analyzed and finally related to one quantitative output of the same system, the so called functional unit; (3) the impact assessment, which strives to evaluate the significance of the environmental impacts contained in a life cycle inventory and helps to determine the relative importance of each of these inventory items; and (4) the interpretation step in which the results are evaluated and compared with the defined goals in order to draw conclusions and formulate recommendations. In this study, modelling was performed using the LCA software SimaPro 7.1.8 [43] including the life cycle inventory (LCI) database Ecoinvent 2.0 [37]. Characterization factors for the impact assessment were obtained from the life cycle impact assessment method ReCiPe 2008 [44].

3.1. LCA goal and scope definition

The goal of the presented study is to assess the life cycle of a low-enthalpy, shallow and vertical GSHP system. The life cycle includes the manufacturing of the heat pump, site preparation and drilling of the borehole, transportation of equipment to the site, installation of borehole heat exchanger and the heat pump, as well as operation and disposal of the GSHP system. The focus is on the geothermal heat extraction technology, and thus further elements of a space heating or air conditioning system are not considered for this assessment. However, it has to be noted that such low-enthalpy technology is ideally combined with an underfloor heating system as well as auxiliary boilers or buffer tanks [45,46]. Jenkins et al. [21] conclude in their assessment that the specific requirements of horizontal-loop GSHP systems for the heat distribution systems can represent a crucial hindrance when replacement of fossil-fuel based heat generators is considered. Requirements such as comparatively high temperatures in radiators reduce the COP and thus the environmental and economic performance. These aspects have to be taken into account when comparing different energy systems, or when planning a replacement of conventional technology with GSHP systems.

Fig. 1 illustrates the main life stages of a GSHP system. There is the initial situation, where no GSHP system is installed or other technologies provide heating and cooling for the residence. For the site preparation the drilling equipment is transported to the property and the borehole that takes up the heat exchanger is drilled. The heat pump is delivered to the site and there connected to the borehole heat exchanger (BHE) and the electricity grid. During operation the system needs low voltage electricity to run the heat carrier liquid circulation pump and the heat pump refrigerant cycle [45,46]. Because of slight continuous leakage, the volatile heat pump refrigerant commonly has to be annually refilled [47]. At the end of the life cycle, the so-called disposal phase, metal parts of the heat pump are completely recycled, the heat pump refrigerant is reused, and the heat carrier liquid is extracted from the BHE tubes and treated in a waste water treatment plant. For the current study we assume that the tubes of the BHE are sealed and left in the ground.

The system boundaries delineate the scope of the LCA. Since a fundamental of LCA is to literally characterize the full life of the studied subject, in each life stage there are various flows from and to the bio- and the technosphere crossing the boundaries of the system. The quantities of these flows are defined by the functional unit (FU), which represents a reference flow to which all other flows (inputs and outputs) of the system are related. The main function of the GSHP system is the provision of heat and

Table 2
Assumed site-specific conditions and technical details of the installed GSHP systems for the base case (calculated for the reference locality Weihenstephan in South Germany using the software programmes CASAnova and Earth Energy Designer, EED), warm case (Madrid, Spain) and cool case (Karlstad, Sweden) for the heating demand of a 200 m^2 single family home.

Parameter	Base case	Warm case	Cool case
Average annual air temperature (°C)	8.3	14.2	6.4
Heating capacity [kW]	10.0	7.2	11.0
Cooling capacity [kW]	6.0	7.6	6.0
Energy demand for heating [MWh/a]	18	6.8	22.8
Energy demand for cooling [MWh/a]	0.9	4.3	0.5
Operating hours of the heat pump per year [h/a]	1800	940	2070
Total duration of the passive cooling per year [h/a]	150	570	85
Number and length of the borehole heat exchanger(s)	2 × 85 m	1 × 100 m	2 × 112 m

cooling. Therefore, in the current study the functional unit is defined as the produced heat of the GSHP system over its entire life span of 20 years. Heat production in cold seasons is combined with a specified rate of cooling power output during the warm season. The GSHP system is thought to be built for a single housing application, which has a heating demand of 10 kW. In addition, the cooling power output for passive cooling in summer is assumed to be 5 kW. The heat pump unit size of 10 kW is intentionally set slightly lower than the average values reported by [1] with 12 kW and in [9] with 11 kW, considering progress in building technology and a decreasing energy demand of houses in the future.

3.1.1. *Base case and other scenarios*

It is difficult to draw general conclusions based on a single specific case study. Suitable borehole configuration and heat pump operation strategy for one particular building depend on factors such as seasonal temperature variation, ground temperature and technical features of the GSHP (Table 1). In order to span a representative range of possible conditions in Europe, various dissimilar scenarios are considered in this study. Special attention is given to the type of primary energy used to operate the heat pump. Therefore, also the role of the different energy mixes of European countries is discussed.

All scenarios are based on a house with a living space of 200 m^2. The annual energy requirements of this type of house under different climatic conditions are computed by the program CASAnova (v. 3.3.03) [48]. To reflect central European conditions, a representative "base case" is set up that is oriented in southern Germany (Table 2). Heating requirements are lower in warmer climates, whereas passive cooling is applied for longer duration. Such conditions are reflected by the "warm case" that is simulated for the city of Madrid (Spain). In contrast, relatively long heating periods as common in Sweden are reflected by the "cool case". The predicted annual heating/cooling requirements are used as input for Earth Energy Designer (EED, v. 3.1) [49], which is a well established and commonly used program for BHE configuration planning. It is assumed that ground properties are the same at each location (mean heat conductivity: 2.3 W/(m K) and mean heat capacity: 2.2 MJ/(m^3 K)). Furthermore, the borehole diameter is set as 135 mm, and the flow rate in the BHE to be 1.7 m^3/h. The life span of the heat pump is expected to be 20 years, and the COP is assumed to be at 4 (at B0/W35 norm conditions for 0 °C brine temperature and 35 °C flow temperature at underfloor heating). These are typical average numbers as reported in various studies (Table 1).

Additionally to these cases, the following three worst case scenarios are defined to conduct a sensitivity analysis. Worst case scenario 1: complete leakage of the heat carrier fluid into the surrounding soil/aquifer. Worst case scenario 2: complete leakage of the volatile heat pump refrigerant due to inappropriate recovery at the end of life. Worst case scenario 3: a degradation of COP from

Table 3
Life cycle inventory (LCI) for the base case of the studied GSHP system [37]. Note that direct emissions to soil at the installation site are not assumed for the base case, but leakage is accounted for in worst case scenario 1 (CH = Switzerland; DE = Germany; GLO = Global; RER = Europe; UCTE = Union for the Coordination of Transmission of Electricity [new denomination is Continental Europe]).

Unit process	Unit	Amount
Known inputs from nature		
Water, unspecified natural origin	[m^3]	12.7
Known inputs from technosphere		
Electricity, low voltage, production (UCTE), at grid	[kWh]	90,000
Electricity, medium voltage, production (UCTE), at grid	[kWh]	128.3
Natural gas, burned in industrial urnace >100 kW (RER)	[MJ]	1,400
Refrigerant HFC-134a, at plant (RER)	[kg]	6.69
Tube insulation, elastomer, at plant (DE)	[kg]	10
Copper, at regional storage (RER)	[kg]	22
Polyvinylchlorid, bulk polymerised, at plant (RER)	[kg]	1
Steel, low-alloyed, at plant (RER)	[kg]	20
Reinforcing steel, at plant (RER)	[kg]	108
Lubricating oil, at plant (RER)	[kg]	1.7
Bentonite, at processing (DE)	[kg]	209
Polyethylene, LDPE, granulate, at plant (RER)	[kg]	204
Ethylene glycol, at plant (RER)	[kg]	119.8
EDTA, ethylenediaminetetraacetic acid, at plant (RER)	[kg]	1.23
Potassium hydroxide, at regional storage (RER)	[kg]	1.23
Cement, unspecified, at plant (CH)	[kg]	33
Transport, freight, rail (RER)	[tkm]	79.6
Transport, van <3.5 t (CH)	[tkm]	100.8
Transport, lorry 3.5–20 t, fleet average (CH)	[tkm]	1,321.6
Diesel, burned in building machine (GLO)	[MJ]	13,587
Emissions to air		
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	[kg]	4.3
Heat, waste	[kWh]	360,000
Emissions to soil		
Ethylene glycol	[kg]	0
EDTA	[kg]	0
Potassium hydroxide	[kg]	0
Polyhexamethylene biguanide	[kg]	0
Known outputs to technosphere		
Disposal, plastics, mixture, 15.3% water, to municipal incineration (CH)	[kg]	11
Disposal, inert waste, 5% water, to inert material landfill (CH)	[kg]	6,501
Treatment, heat carrier liquid, 40% $C_3H_8O_2$, to wastewater treatment, class 2 (CH)	[m^3]	0.36

Table 4

Production, grid and transformation CO_2 eq emissions for low voltage electricity production and consumption (production + import) mixes of the ENTSO-E countries excluding the Baltic countries due to lack of data.

Country	Code	Coal [%]	Oil [%]	Natural gas [%]	Nuclear [%]	Hydropower [%]	Geothermal [%]	Photovoltaics [%]	Wind power [%]	Biomass [%]	Biogas [%]	Other [%]	Low voltage production, at grid [kg CO_2 eq/kWh]	Imports [%]	Main import countries	Low voltage production, at grid + imports [kg CO_2 eq/kWh]
Austria	AT	9.4	2.1	13.0	–	46.4	0.0	0.0	1.2	0.8	0.2	6.1	0.353	20.8	CH, CZ, DE, HU, SI	0.442
Bosnia	BA	44.5	–	0.9	–	42.6	–	–	–	–	–	0.0	0.948	12.0	HR, ME	0.934
Belgium	BE	9.1	1.7	21.4	46.6	1.7	–	–	0.2	0.5	0.2	3.5	0.363	15.1	FR, NL, LU	0.366
Bulgaria	BG	44.2	1.9	3.5	39.7	8.4	–	–	–	–	–	0.5	0.786	1.9	GR, ME, RO	0.788
Switzerland	CH	–	1.3	1.0	26.1	31.8	0.0	0.0	0.0	0.0	0.0	0.9	0.029	38.8	AT, DE, FR, IT	0.134
Czech Republic	CZ	52.1	0.4	4.0	28.6	3.0	–	–	–	0.6	0.1	0.1	0.882	11.1	AT, DE, PL, SK	0.923
Germany	DE	43.5	1.5	9.3	25.1	4.4	–	0.1	4.0	0.6	0.5	2.5	0.743	8.6	AT, CH, CZ, DK, FR, NL	0.719
Denmark	DK	38.4	3.4	20.5	–	0.1	–	–	14.4	3.8	0.5	0.0	0.767	19.0	DE	0.619
Spain	ES	27.2	8.2	19.0	22.1	12.3	–	0.0	5.6	1.5	0.5	0.7	0.602	2.9	FR, PT	0.592
Finland	FI	16.6	0.6	12.9	23.3	15.6	–	–	0.1	10.3	0.0	7.6	0.497	13.0	NO, SE	0.339
France	FR	4.4	1.0	3.1	76.8	11.5	–	–	0.2	0.2	0.1	1.1	0.105	1.6	BE, CH, DE, ES	0.108
Great Britain	GB	32.6	1.1	39.9	19.1	1.3	–	–	0.5	1.0	–	2.0	0.698	2.5	FR	0.683
Greece	GR	54.3	12.9	13.8	–	8.6	–	0.0	1.8	–	0.2	0.2	1.176	8.1	BG, IT, MK	1.144
Croatia	HR	7.7	5.5	8.2	10.4	28.3	–	–	–	0.0	–	0.0	0.421	39.9	BA, HU, ME, RS, SI	0.594
Hungary	HU	18.2	1.7	26.0	26.4	0.5	–	0.0	–	1.5	0.1	0.4	0.830	25.2	AT, HR, ME, RO, RS, SI	0.747
Ireland	IE	28.2	11.7	47.2	–	3.8	–	–	2.7	0.0	0.4	0.0	0.896	6.0	GB	0.884
Italy	IT	12.4	13.1	37.3	–	14.7	1.5	0.0	0.6	0.4	–	6.2	0.716	13.8	AT, FR, GR, SK, CH	0.641
Luxembourg	LU	–	–	27.9	–	8.5	–	–	0.5	–	0.2	0.7	0.599	62.3	BE, DE	0.639
Montenegro	ME	19.1	–	–	–	25.3	–	–	–	–	–	0.0	0.736	55.6	BA, RS	0.907
Macedonia, FYR	MK	57.5	0.1	–	–	18.0	–	–	–	–	–	0.0	1.289	24.5	GR, ME, RS	1.275
Netherlands	NL	19.1	2.3	49.6	3.3	0.1	–	–	1.6	1.5	0.2	4.0	0.742	18.2	BE, DE	0.725
Norway	NO	0.0	0.0	0.3	–	86.8	–	–	0.2	0.2	–	0.3	0.017	12.2	DK, FI, SE	0.046
Poland	PL	88.4	1.6	2.0	–	2.5	–	–	0.1	0.5	0.1	1.4	1.360	3.6	CZ, DE, SK	1.188
Portugal	PT	27.3	10.5	21.5	–	19.2	0.2	0.0	1.6	2.3	0.0	1.0	0.711	16.5	ES	0.693
Romania	RO	36.1	3.7	17.6	9.4	29.6	–	–	–	–	–	0.5	0.804	3.2	BG, HU, ME, RS	0.806
Serbia	RS	65.9	–	–	–	22.5	–	–	–	–	–	0.0	1.260	11.1	BA, BG, HU, ME	1.220
Slovenia	SI	24.1	0.2	1.7	13.6	21.0	–	–	–	0.4	0.1	0.0	0.557	38.8	AT, HR, IT	0.485
Slovakia	SK	11.4	1.5	4.9	34.2	9.1	–	–	–	0.0	0.0	0.9	0.411	38.1	AT, CZ, PL,	0.502
Sweden	SE	0.6	1.2	0.5	45.7	36.3	–	–	0.6	3.9	0.0	1.7	0.052	9.5	DE, DK, FI, NO, PL	0.105
Continental Europe		30.4	4.4	16.1	30.8	12.7	0.2	0.0	2.1	0.7	0.2	2.4	0.599	–		–

Sources: [54,69].

4 to 3 due to misjudgment of underground conditions and/or inadequate adjustments of the heat pump system.

3.2. Life cycle inventory

In the life cycle inventory (LCI) phase of LCA, information about the unit processes of the product system is collected, analyzed and finally quantitatively related to the functional unit. As described in the following sections, data used here was collected from different sources. In particular, a GHP dataset provided by Ecoinvent served as the basis [37]. The dataset was thoroughly analyzed, modified and completed with custom and calculated data. From this set, a parameterized model was built to generate GSHP datasets for all cases and scenarios. Table 3 shows the established LCI for the base case of the studied GSHP system.

The inventory of the GSHP system is divided into following subgroups.

3.2.1. Borehole, borehole heat exchanger and heat carrier liquid

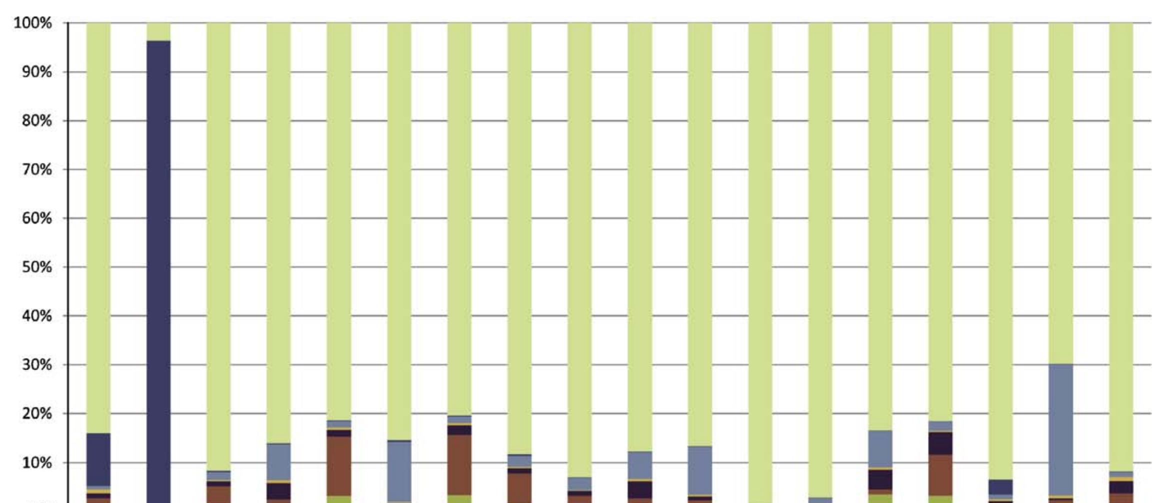
In the base case, the heat is extracted from the ground by means of two borehole heat exchangers with a depth of 85 m each. The boreholes are drilled by flush or sledge hammer technique, consuming 1.5 or 2.5 l of diesel per meter, respectively. In the inventory a value of 2.1 l/m was used, accounting for the market shares of the two drilling techniques of 40% and 60% [37]. For the backfilling of the borehole, a cement–bentonite suspension is typically used or even required in many countries. In some countries however, for example in Sweden, no backfilling is usually applied. The BHE often consists of double U-shaped polyethylene tubes, which are usually filled with a heat carrier liquid. In the water protection zone III, for example in Germany, only water is approved to be filled into the BHE. In order to determine potential toxicity and environmental impacts, the exact composition of the heat carrier liquid has to be known. From product and material safety data sheets of the common commercial heat carrier liquid product Pekasol L the following components were identified [50–52]: 75.0% water, 24.25% organic glycol as antifreezing compound (i.e. ethylene- or propylene glycol) and only 0.75% additives. The additives might be 0.25% ethylenediaminetetraacetic acid (EDTA), a water hardness stabilizer, 0.25% polyhexamethylene biguanide (PHMB), a biocide, and 0.25% potassium hydroxide or molybdate (KOH and MoO_4^{2-}), corrosion inhibitors. Table 3 lists all emissions and consumptions related to the individual compounds.

3.2.2. Heat pump and heat pump refrigerant

The heat pump mainly consists of copper and steel. The tubing and electric cables are insulated with elastomer and PVC. During the manufacturing process medium voltage electricity and heat from natural gas in the order of 460 and 1400 MJ are needed. These unit process values were taken from the original Ecoinvent dataset [37]. Crucial for the transmission of heat from the ground to the heating system is the heat pump refrigerant. In this study the refrigerant was assumed to be the common R134a. This compound is also the main ingredient for other refrigerants such as R407c. An amount of 0.3 kg refrigerant per kW is needed to run the heat pump. This is an average value from test results of the Swiss heat pump test center [53]. There are average refrigerant losses of 3% during manufacturing and 6% per year during operation. At the end of the life time of the heat pump, steel and copper are recycled and R134a is reused. Another 20% of R134a is lost during the disposal of the heat pump.

3.2.3. Transports

For the current study we assume that the heat pump is transported by train over a distance of 600 km and by lorry over a distance of 50 km. Furthermore, the drilling machine and the



Technogical Elements / Midpoint Categories	Climate Change [t CO_2 eq]	Ozone Depletion [g CFC-11 eq]	Terrestrial Acidification [kg SO_2 eq]	Freshwater Eutrophication [kg P eq]	Marine Eutrophication [kg N eq]	Human Toxicity [kg 1,4-DB eq]	Photochemical Oxidation Formation [kg NMVOC]	Particulate Matter Formation [kg PM10 eq]	Terrestrial Ecotoxicity [kg 1,4-DB eq]	Freshwater Ecotoxicity [kg 1,4-DB eq]	Marine Ecotoxicity [kg 1,4-DB eq]	Ionising Radiation [t U235 eq]	Agricultural Land Occupation [m^2a]	Urban Land Occupation [m^2a]	Natural Land Occupation [m^2a]	Water Depletion [m^3]	Metal Depletion [t Fe eq]	Fossil Depletion [t Oil eq]
Electricity	53.5	2.63	228.3	0.93	12.72	4'139.9	113.5	71.6	5.5	55.7	85.2	41.94	770.6	216.3	6.0	435.9	2.41	15.50
Heat Pump Refrigerant	6.8	69.57	0.7	0.00	0.03	14.5	0.3	0.2	0.0	0.1	0.1	0.01	0.7	0.2	0.0	14.5	0.00	0.02
Heat Pump	0.4	0.04	4.0	0.08	0.19	590.5	1.8	1.9	0.1	3.5	9.7	0.11	9.5	19.1	0.1	4.4	0.93	0.17
Heat Carrier Fluid	0.5	0.01	0.7	0.01	0.09	13.9	0.7	0.3	0.0	0.3	0.4	0.09	3.7	1.0	0.0	2.0	0.02	0.14
Borehole Heat Exchanger	0.6	0.05	2.6	0.04	0.21	30.1	2.8	0.9	0.1	2.2	0.8	0.04	5.2	10.5	0.3	6.0	0.01	0.43
Borehole	1.2	0.16	10.1	0.02	1.89	27.9	17.2	5.1	0.1	1.0	1.3	0.04	1.7	2.6	0.6	1.9	0.05	0.44
Transport	0.5	0.08	2.8	0.01	0.50	25.6	4.8	1.2	0.1	0.7	0.9	0.07	2.0	9.2	0.2	1.9	0.03	0.19
Total	**63.7**	**72.5**	**249.1**	**1.09**	**15.62**	**4'842.3**	**141.1**	**81.1**	**5.9**	**63.5**	**98.4**	**42.30**	**793.5**	**258.8**	**7.3**	**466.6**	**3.46**	**16.88**

Fig. 2. Relative contributions of a technological element to the ReCiPe 2008 midpoint categories under hierarchist's perspective (base case, assuming average continental European electricity mix).

materials for the site preparation are transported in a 16 t lorry over a distance of 180 km. The transport distance of the cement–bentonite suspension is assumed to be 300 km. All these distances are standard transport distances as used in the Ecoinvent datasets [37].

3.2.4. Electricity

During operation the GSHP system needs low voltage electricity to run the heat pump refrigeration cycle and the heat carrier liquid circulation. The amount of electricity depends on the heating demand of the building. For the current base case the average electricity mix of Continental Europe with a carbon footprint of 0.599 kg CO_2 per kWh is used. The average is weighted by the yearly countries' electricity production. Continental Europe (former UCTE) is one of five regional groups of the European Network of Transmission System Operators for Electricity (ENTSO-E). The other four regional groups are called Nordic, Baltic, UK, and Ireland [54]. Table 4 shows the carbon emissions of the electricity mixes of all ENTSO-E countries in 2006, excluding the Baltic regional group. The Continental European energy mix is applied for low voltage electricity need for the operation of the GSHP system as well as for the medium voltage electricity demand of the heat pump manufacturing.

The life cycle heating energy demand for the base case is 360 MWh with a total operating time of 1800 h per year. For a COP of 4, this means an electricity demand of 90 MWh over 20 year. Accordingly, the amount of geothermal heat extracted from the ground is 270 MWh.

3.3. Life cycle impact assessment

Life cycle impact assessment (LCIA) is conducted in order to connect each inventory analysis result to the corresponding environmental impact. In the impact assessment phase the inventory table including the list of emissions, resources and wastes associated with the studied product is converted into a smaller number of indicators (Table 3). To achieve that, ISO 14042 defines the following steps: selection and definition of the impact categories of interest, assignment of the inventory data to the chosen impact categories (*classification*), and calculation of impact category indicators using characterization factors (*characterization*) [55].

In this study the LCIA method ReCiPe 2008 was applied [44]. ReCiPe 2008 is a standardized method that uses harmonized category indicators of the midpoint and the endpoint level and includes 18 midpoint impact categories (Fig. 2) aiming at modelling damage to three areas of protection: (i) damage to human health, (ii) to ecosystem quality and (iii) to natural resources. If needed, the results for these three categories can be further combined into a single score using default weighting factors. This final score is expressed as eco-points, where one point can be interpreted as one thousandth of the annual environmental load of one average European inhabitant.

Impact assessment according to ReCiPe 2008 is performed in two steps: (i) the actual damage modelling and (ii) the normalization and weighting. Damage modelling in terms of human health and ecosystem quality is based on fate-, exposure-, effect-, and damage analysis resulting in scores expressed as disability adjusted life years (DALY) and loss of species during a year (species $\times$ yr), respectively. Normalization factors in ReCiPe 2008 were calculated and implemented according to Sleeswijk et al. [56]. In the weighting step, the method uses a panel approach aiming to reflect the society's view on which damages or potential impacts are of greatest importance. According to this cultural perspectives theory [57], consistent sets of subjective choices on time horizon and age weighting can be grouped around three perspectives, identified by the following names: individualist (I), hierarchist (H) and egalitarian (E). Weighting factors were calculated and implemented as described by the LCIA method Eco-indicator 99 [58]. The H (Hierarchist) perspective is chosen as default, while the other perspectives (I and E) can be used in a robustness analysis.

As characterization factors were not available for additives (EDTA, KOH and PHMB), these were developed according to the ReCiPe 2008 methodology. Fate, exposure, and effect factors were calculated using the standardized LCIA models USES-LCA 2.0 [59] and USEtox [60]. Physico-chemical properties and information on environmental persistence and toxicity were obtained from product- and material safety data sheets of the commercial antifreeze product Pekasol L [50–52] and the chemical database EPI SuiteTM [61].

4. Results, interpretation and discussion

4.1. Base case

The life cycle inventory of the base case is assessed with the 18 ReCiPe midpoint impact categories in a hierarchist perspective. Fig. 2 shows the relative contributions of the seven distinguished technological elements to the total scores within each category. The absolute values are given in the table below the graph. Note that at the first stage of the assessment, no cross comparison or relative ranking of the different impact categories is intended, but rather a concurrent analysis of the technological factors that are most relevant for different safeguard subjects.

Electricity for heat pump operation dominates 17 out of 18 categories and contributes between 70% and 99% to the total score. The Continental Europe electricity is a mix of 30.8% nuclear, 30.4% coal, 16.1% natural gas, 12.7% hydropower and 10% other electricity sources (Table 4). Thus, it affects most the ecosystem quality (coal, natural gas), the damage to human health (coal, nuclear power), and natural resources categories (coal, nuclear power). The ozone depletion category on the other hand is dominated by the heat pump refrigerant, R134a. The refrigerant itself is no ozone depleting substance, but during the manufacturing of the precursor substances, trichloroethylene and tetrachloroethylene, significant amounts of chlorinated hydrocarbons (i.e. mainly CFC-12) may be emitted. Also, R134a has a significant global warming potential (GWP) of 1430 kg CO_2 eq and therefore contributes by about 10% to the climate change category.

The heat pump has its largest shares in the human toxicity and metal depletion categories due to extraction and processing of copper in the background processes. The heat carrier fluid is only of minor significance in all categories, whereas the borehole heat exchanger contributes up to 4.5% to the different categories. The borehole, receiving the BHE, contributes most to the categories marine eutrophication, photochemical oxidation formation, and natural land transformation. These shares of up to 12% stem entirely from borehole drilling by using a diesel burning drilling machine. The transport of the heat pump system and building equipment to the construction site is of minor relative importance and mainly attributed to the use of fuel and roads.

The individual midpoint categories of ReCiPe 2008 can be aggregated to the single score. Thus, a relative appraisal of the total adverse environmental effects of the seven technological elements is possible. The calculated single score for the base case is 5257 Pt (H) (i.e. ecopoints under hierarchist perspective). The ecopoints could be interpreted as follows: for the time period of 20 years and assuming a family of four occupants 6.6% of the personal annual environmental impact is produced on the average by the GSHP system.

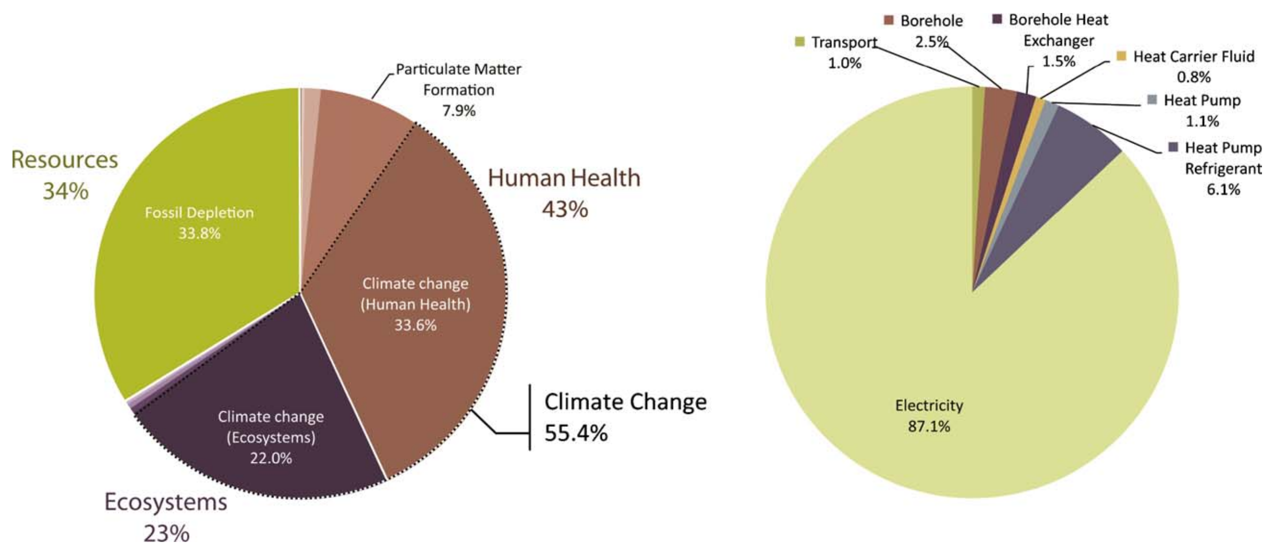


Fig. 3. Relative contributions of the impact categories and the technological elements to the ReCiPe 2008 single score under hierarchist's perspective (base case, assuming average continental European electricity mix).

Fig. 3 depicts the relative environmental effects with respect to the impact categories. The human health damage categories contribute 43% to the total ReCiPe single score, resource depletion 34%, and ecosystem damage 23%. The main categories are fossil depletion (33.9%), climate change impacts to human health (33.5%) and ecosystem (21.9%), followed by particulate matter formation (7.9%). Thus, climate change has an overall contribution of 55.4%. The findings do not change significantly by applying a egalitarian or individualist perspective.

Electricity contributes 87.1% to the single score and is the main contributor to environmental impacts of the GSHP system. In contrast, heat pump, transport and heat carrier liquid contribute only between 0.8% and 1.1%. The rest is shared among borehole, BHE and heat pump refrigerant (6.1%). Robustness analysis has shown that the latter is ranked second under individualist's perspectives with 13.1%. Under the egalitarian perspective the heat pump refrigerant (1.8%) is considered less important than the BHE and the borehole. This is because this perspective gives more weight to land use categories, in which the heat pump refrigerant life cycle has only a minor share.

4.2. Sensitivity analysis

Based on the impact assessment results of the base case scenario, the four most important impact categories (climate change, fossil depletion, particulate matter formation, and freshwater ecotoxicity) were chosen to conduct a sensitivity analysis. Freshwater ecotoxicity was selected to indicate the changes due to leakage of the heat carrier fluid. The three worst case scenarios as defined in Section 3.1 were combined with four different country electricity mixes. Besides the Continental European mix, the electricity mixes from Germany (DE), Poland (PL), and Switzerland (CH) were chosen. Germany's electricity mix was selected as a reference to the low carbon electricity mix of Switzerland and the carbon intensive electricity mix of Poland. Fig. 4a–d shows the impact assessment results for the sensitivity analysis.

The CO_2 emissions of the base case for the studied GSHP system vary between 22 t CO_2 eq for Switzerland and 117 t CO_2 eq for Poland for a considered life cycle of 20 years. The Continental Europe mix is in between at around 63 t CO_2 eq. The GSHP system operated in Germany generates 75 t CO_2 eq over its life cycle. The leakage of the heat carrier fluid causes no further CO_2 emissions. In contrast, the leakage of the volatile heat pump refrigerant is responsible for additional 3.4 t CO_2 eq emissions. These emissions have highest relative impact in countries with low carbon electricity mixes (+15.5% CO_2 eq emissions for CH), but less for carbon intensive mixes (+2.9% CO_2 eq emissions for PL). The degradation of COP from 4 to 3 is most influential for life cycle CO_2 emissions. It causes additional relative emissions between 18% (CH) and 30% (PL).

Only worst case scenario 3 induces an increased fossil depletion, whereas for the other worst case scenarios the impacts in this category remain the same. The degradation of COP from 4 to 3 causes an increase in fossil depletion from 24% (CH) to 31% (Continental Europe, DE, PL). The results appear to be similar for the impact category of particulate matter formation, where the increases for worst case scenario 3 are between 20% and 31%. This category denotes organic and inorganic airborne emissions ($<10\ \mu m$) that stem mainly from combustion. The country ranking for fossil depletion is the same as for climate change: CH, Continental Europe, DE, and PL. However, the ranking changes for particulate matter formation and terrestrial ecotoxicity, for which Germany has lower emissions than Continental Europe. It can be said that the two categories fossil depletion and particulate matter formation are, in addition to changes in electricity demand, both highly sensitive to changes in electricity mix.

The impact category freshwater ecotoxicity was chosen to illustrate the impacts of a total leakage of the heat carrier fluid into soil and aquifer. For electricity mixes mainly based on carbon fuels a degradation of COP is worse for the freshwater ecology than the leakage of heat carrier fluid. For Switzerland, the difference between worst case scenario 3 and worst case scenario 1 is much smaller. However, it must be mentioned that the first denotes damage to freshwater ecosystems somewhere in the world and the other has a direct local impact on the aquifer. Therefore, it is also a question of perspective and weighting, which impact is to be considered worse.

4.3. Comparison to conventional heating systems

As reviewed above, the environmental benefits from GHP systems commonly are judged by the CO_2 eq savings potential calculated in comparison to conventional heating (and cooling) systems such as oil burner and gas furnace [1,9,11]. Due to country-dependent electricity mixes and regionally variable climatic conditions, the base case provides insight into average potential CO_2 eq savings in Europe, but is not representative for country-

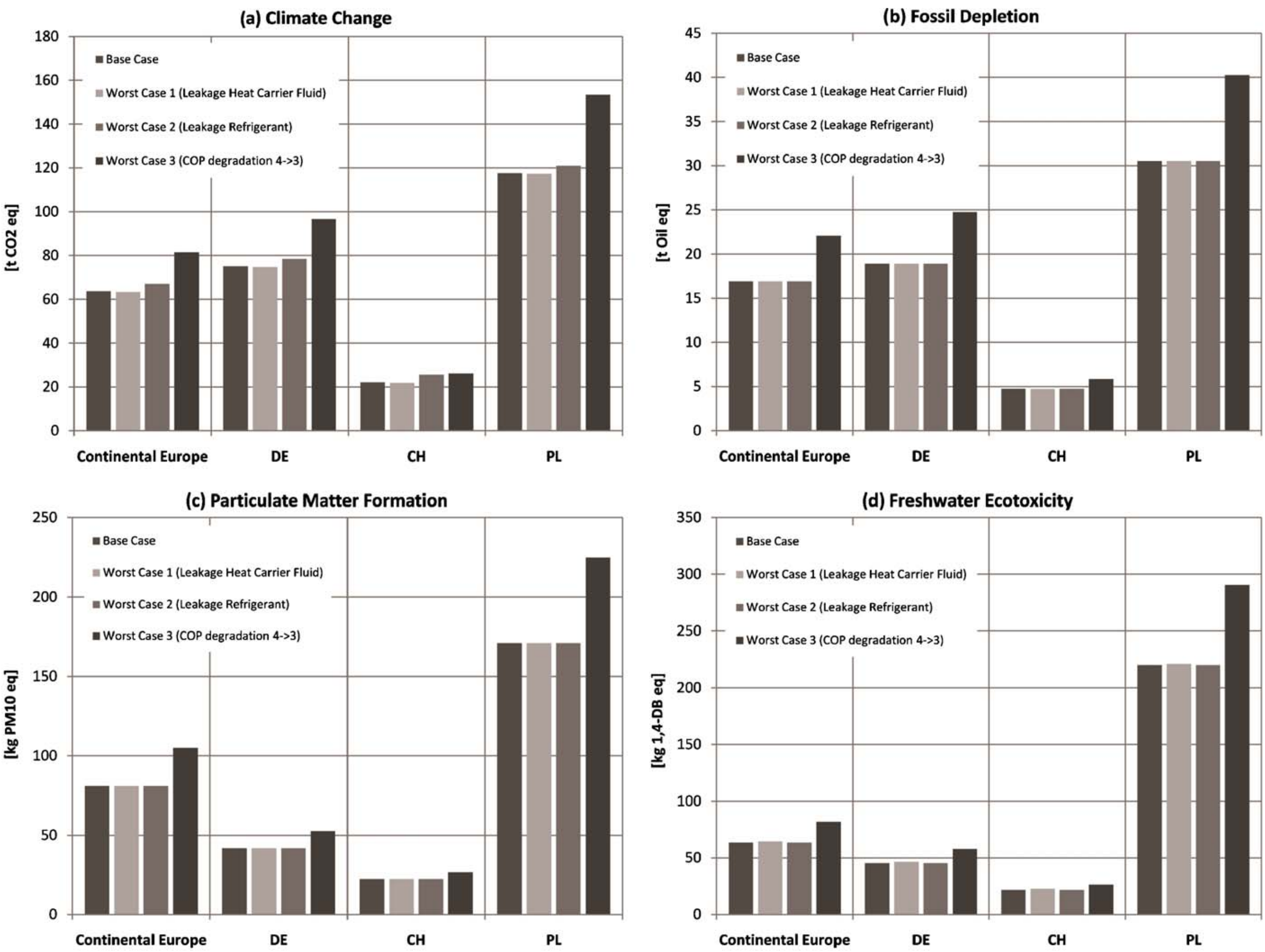


Fig. 4. Base case and three worst case scenarios applied on four different electricity mixes (Continental Europe, DE: Germany, CH: Switzerland, PL: Poland) for the four main impact categories (climate change, fossil depletion, particulate matter formation and freshwater ecotoxicity).

specific conditions and different heating/cooling requirements. Therefore, additionally the "warm case" and "cool case" have been defined. Although they were calculated for a specific location, their characteristics were thought to be generally applicable for various European countries. CO_2 eq emissions are computed for all ENTSO-E countries (excl. the Baltic states) for the GSHP systems as defined in Table 2, and compared to conventional heating systems. The chosen conventional technologies represent the best available technique (i.e. condensing, non-modulating oil boiler; condensing, modulating gas furnace). Comparison is made without taking into account technology-specific requirements to the heating system (e.g. suggested combination of underfloor heating and GSHP).

The percentage values listed in Table 5 show CO_2 eq savings achieved by selecting a GSHP system instead of a conventional heating system without considering cooling services. Negative values denote cases where more CO_2 eq are emitted with a GSHP system than with a conventional heating system. The values in brackets are CO_2 eq savings that can be achieved when including the effect of passive cooling provided by GSHP systems, as compared with a conventional heating system which is expanded to include the provision of cooling via an air conditioning system. The air conditioning was modeled with the dataset of an air/water heat pump. The datasets for the heating and the air conditioning systems were taken from the Ecoinvent database and as far as possible adapted to specific country conditions (i.e. electricity mix, oil and natural gas provision).

In countries with low-carbon electricity mixes such as Switzerland, France, Norway and Sweden, CO_2 eq savings for the base case of 81–87% can be achieved, when compared to oil heating. For the warm case savings are still between 73% and 79%. In comparison to gas furnace heating the values range from 76% to 83% for the base case, and from 66% to 72% for the warm case. The savings achieved in comparison to gas furnaces are always smaller than to oil boilers.

Greece, the former Yugoslav Republic of Macedonia, Poland and Serbia have the most carbon intensive electricity mixes. In these countries conventional heating systems are favorable, because GHG emissions for the GSHP system are higher. However, this holds only true if the passive cooling capabilities of GSHP systems are neglected. If passive cooling is considered for the warm case, the CO_2 savings reach 37–42%. In the conventional case, cooling would have to be provided by air conditioning systems, which need far more electricity than the circulation pump of the GSHP system. These values emphasize the advantage of GSHP systems to be used both for (active) heating and (passive) cooling, depending on the specific location.

The median CO_2 savings for all countries are between 30% and 39% compared with oil heating and 11–23% compared with gas furnaces. These values can reach 55% in the warm case when also air conditioning is considered. When compared to previous case studies and calculations from other studies (Table 1) [1], these median values are slightly lower. This may be attributed to the fact

Table 5
Savings of CO_2 eq emissions in percentage [%] for the base case, the warm case, and the cool case compared with oil boiler and gas furnace heating. The savings including passive cooling of the GSHP system are shown in brackets.

Country	Code	Compared with oil boiler heating (and air condition cooling)			Compared with gas furnace heating (and air condition cooling)		
		Base case [%]	Warm case [%]	Cool case [%]	Base case [%]	Warm case [%]	Cool case [%]
Austria	AT	56 (58)	49 (63)	57 (58)	53 (54)	44 (60)	54 (54)
Bosnia	BA	19 (24)	12 (48)	20 (22)	13 (18)	5 (46)	14 (16)
Belgium	BE	62 (63)	54 (65)	63 (64)	48 (49)	37 (56)	49 (50)
Bulgaria	BG	30 (33)	22 (52)	31 (33)	25 (29)	17 (50)	26 (27)
Switzerland	CH	81 (81)	73 (77)	82 (82)	76 (76)	66 (71)	77 (77)
Czech Republic	CZ	20 (24)	12 (48)	21 (23)	12 (17)	3 (45)	13 (15)
Germany	DE	35 (38)	28 (54)	36 (37)	21 (25)	11 (47)	22 (24)
Denmark	DK	43 (45)	35 (57)	44 (45)	22 (26)	11 (47)	23 (25)
Spain	ES	45 (47)	37 (57)	46 (47)	31 (34)	21 (50)	32 (33)
Finland	FI	64 (65)	57 (67)	65 (66)	62 (63)	54 (65)	63 (63)
France	FR	82 (83)	75 (78)	83 (83)	79 (79)	69 (73)	80 (80)
Great Britain	GB	38 (41)	30 (55)	39 (40)	12 (17)	1 (44)	13 (15)
Greece	GR	4 (10)	−4 (44)	5 (8)	−2 (4)	−11 (42)	−2 (2)
Croatia	HR	45 (47)	37 (57)	46 (47)	40 (43)	32 (55)	41 (42)
Hungary	HU	33 (36)	25 (53)	34 (35)	28 (32)	20 (51)	29 (31)
Ireland	IE	23 (27)	15 (49)	24 (26)	−6 (2)	−16 (40)	−4 (−1)
Italy	IT	41 (44)	33 (56)	42 (43)	28 (32)	19 (50)	29 (31)
Luxembourg	LU	41 (44)	34 (56)	42 (43)	19 (23)	8 (46)	20 (22)
Montenegro	ME	21 (25)	14 (49)	22 (24)	15 (20)	6 (46)	16 (18)
Macedonia, FYR	MK	−5 (2)	−13 (41)	−5 (−1)	−14 (−6)	−22 (39)	−13 (−9)
Netherlands	NL	35 (38)	27 (53)	36 (37)	9 (14)	−2 (43)	10 (12)
Norway	NO	87 (87)	79 (81)	88 (88)	83 (83)	72 (75)	84 (84)
Poland	PL	1 (8)	−6 (43)	2 (5)	−21 (−12)	−31 (37)	−20 (−16)
Portugal	PT	37 (40)	30 (54)	38 (39)	21 (25)	11 (47)	22 (24)
Romania	RO	29 (32)	21 (51)	30 (31)	20 (24)	11 (48)	21 (23)
Serbia	RS	−1 (5)	−9 (42)	−1 (2)	−15 (−6)	−23 (39)	−14 (−10)
Sweden	SE	83 (83)	75 (78)	83 (84)	76 (76)	65 (71)	77 (77)
Slovenia	SI	53 (55)	45 (61)	54 (55)	50 (52)	42 (59)	51 (52)
Slovakia	SK	52 (53)	44 (60)	52 (53)	49 (50)	40 (59)	50 (50)
Median value		38 (41)	30 (55)	39 (40)	22 (26)	11 (48)	23 (25)

that in the present study only newest generation conventional heating systems are considered for comparison, and that GHG emissions from the full life cycle are calculated for all systems, while previous studies only consider direct emissions from operation.

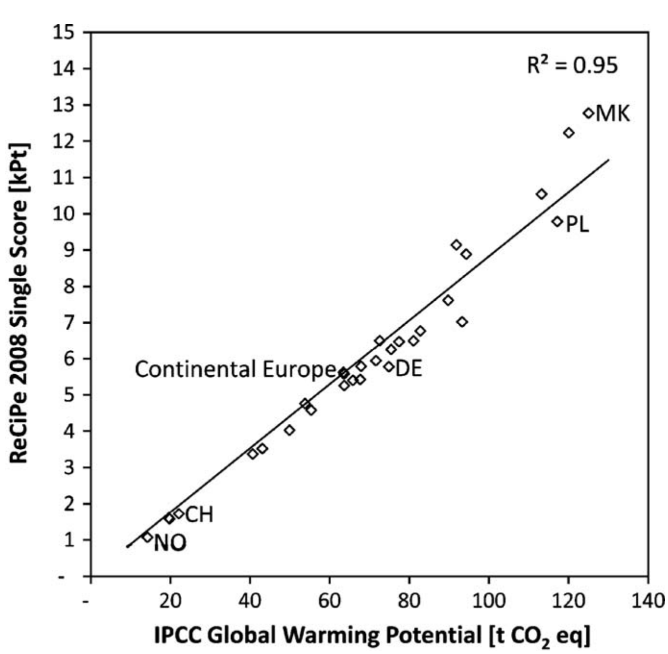


Fig. 5. Correlation of IPCC global warming potential 100 years values of the GSHP system base cases for the ENTSO-E countries with the respective result of the ReCiPe 2008 Single Scores (hierarchist). As examples, Norway (NO), Switzerland (CH), Germany (DE), Poland (PL) and Macedonia (MK) are annotated.

4.4. GHG emissions based assessment versus results from full LCA

Using exclusively the greenhouse gas emissions instead of a more comprehensive LCA to measure and compare the entire environmental impact of GSHP systems is a common simplification. In order to examine whether CO_2 eq (i.e. global warming potential, GWP) is a suitable indicator for the environmental impacts of GSHP systems, the base case GHG emissions for the different European countries are compared to their ReCiPe 2008 single score values. The calculated correlation coefficient is 0.95 (Fig. 5 for the hierarchist's perspective). Especially for countries with low-carbon electricity mixes the GWP is a good indicator for life cycle environmental impacts of GSHP systems. For countries with high shares of electricity production from coal, the type of coal burned (lignite or hard coal) must be considered to make a reliable statement about the expected environmental impacts by using GWP as an indicator. The expected CO_2 emissions from lignite and hard coal are almost the same. However, lignite scores higher in ReCiPe 2008 points, because it is related with higher emissions of particulate matter and larger land use for its extraction. In summary, CO_2 seems to be a suitable indicator to compare GSHP systems with conventional heating and cooling options, but it does not give a holistic view over all different environmental aspects related with GSHP systems.

Although the LCA based analysis represents a holistic view, it is not complete. Among the limitations of available LCA frameworks is that environmental assessment is based on a given set of impact categories. Following given calculation and assessment methodologies is favorable in regards to transparency, acceptance and making general conclusions. However, specific technologies such as GSHP systems may cause burdens not explicitly reflected by standardized concepts. For example, there exists a general gap of

LCA in appropriately reflecting impacts to groundwater (e.g. to groundwater ecology, risk of vertical connection between two aquifer systems [25]). Furthermore, land use impacts are defined with respect to square meters used or consumed during all the life cycle. In fact the most apparent ‘‘land use’’ is the borehole for the BHE. In principle, it covers less than a square meter, but has an enormous vertical extension of up to several hundreds of meters. Such aspects may be even more intricate to be reflected for deep geothermal technologies.

Another point worthy of discussion is the life cycle inventory utilized for the presented study. Although Ecoinvent is one of the most commonly used databases, it mainly reflects European conditions. Assessments might differ, for example for North America; however, it is not expected that differences are fundamental for equally developed countries. Finally, the relative weighting of different impact categories has to be decided from case to case. The presented assessment follows ReCiPe, and highlights the dominant role of GHG emissions. However, GSHP systems may be even environmentally attractive if COP is small, primary energy source is carbon intense and no GHG is saved at all. This is the case for example in China, where GSHP systems are also promoted to reduce fume exposure in large cities. By the increase of GSHP system density, urban particulate matter formation from coal or wood fires is reduced and shifted to remote power plants.

5. Conclusions

Ground source heat pump systems are reputed to be environmentally attractive and renewable technologies. This is mainly attributed to substantial savings in greenhouse gas emissions. The presented review of available predictions, previous studies and reports from case studies shows an average savings in GHG emissions of above 50% in comparison to conventional heating systems. However does this mean also half of the environmental impact? A standardized LCA procedure was applied to a typical central European single family residence, which utilizes the Continental European electricity mix to operate the heat pump of a vertical closed-loop system. We can conclude that in fact CO_2 emissions from primary energy consumption for heat pump operation are most crucial for GSHP systems. Summing all environmental impacts over a life cycle of 20 years, the spent electricity dominates by 87.1%. Continental European electricity mix use means considerable climate change impacts that can be subdivided with respect to their harm on human health and ecosystems. Looking at the ReCiPe results, environmental impacts, however, do not only stem from GHG emissions. About one third of the environmental burden is attributed to fossil energy depletion. A further noteworthy category, although of minor relevance, is particulate matter formation due to burning fossil fuels. In general, however, CO_2 emissions can be considered as a good proxy for environmental assessment of GHP systems.

Due to the role of the primary energy mix, environmental impacts from GHP systems are least in countries with a high share of renewable energy in the electricity mix such as Norway and Switzerland. However, the electricity market is not restricted to a country, and thus electricity trading blurs the differences. Switzerland produces one of the most environmental friendly electricity mixes in Europe, yet electricity imports of around 40% increase the CO_2 emissions per kWh by a factor of 5. This aspect and the fact that renewable energies typically also carry a small, but not negligible environmental impact, makes it impossible to design the GSHP technology entirely free of CO_2 emissions.

The examined hypothetical single family house (base case) would result in GHG emissions for the considered life span of 20 years between 22 t CO_2 eq (Switzerland) and 117 t CO_2 eq (Poland), with an Continental European average of 63 t CO_2 eq. Independent of the setting, the dominating factor is always the consumed electricity. Overestimation or decline of the COP can significantly increase these numbers, of course the most in countries with high CO_2 eq per kWh. Since the COP is mainly controlled by the output temperature, it is desirable to compensate peak heating requirements by auxiliary technologies, which in practice is commonly done for larger shallow geothermal systems (>30 kW). A comprehensive study on different European conditions and countries revealed a significant variability of potential savings of GHG emissions depending on the location of the installed GSHP system. Even if generally valid numbers cannot be derived, we computed median values somewhat lower than predicted in other studies. A major reason for this is that a full LCA is applied here. Using a GSHP system only for heating means an average of 18% savings for all cases in comparison to gas furnace heating and 35% in comparison to oil fired boilers. An attractive feature of a GSHP system that needs more attention in practice is that they can be run in dual mode. By using passive cooling, in particular in warm climates, these savings or reductions can significantly increase when compared to additional air conditioning systems. Since the latter are often economically attractive only in larger buildings, the advantage of GSHP systems in dual mode operation becomes here most apparent.

We further scrutinized the influence of other technological elements, such as borehole construction, heat carrier fluid and heat pump. Of particular interest is the refrigerant used in the heat pump, especially when, as is common, halogenated compounds are applied. These are critical because of their enormous greenhouse potential and the emission of ozone depletion substances, which appear as precursors during manufacture. However, we could show that even substantial leakage of such substances has only a minor impact on the entire environmental evaluation. Meanwhile, more environmentally friendly refrigerants are suggested, such as propane or CO_2, and thus the relative role of this element can be expected to diminish in the future.

Quantification of the overall environmental impact by single scores is only feasible by assigning subjective weights to the different existing impact categories. By comparing different standardized weighting schemes, it was possible to generalize the results. However, for the assessment of an individual case, site-specific considerations may come more into the fore. For example, boreholes represent permanent modifications of natural aquifers, and can cause accidental connections between different aquifer systems. Such special threads are not reflected by the LCA methodology applied. Nevertheless, we shed light on the heat carrier fluid to further investigate the relevance of potential site-specific effects. A worst case scenario is set up, with full leakage of the heat carrier fluid circulated in the borehole heat exchanger. Overall impacts are expressed with respect to freshwater ecotoxicity, and are shown to rise by 14% (PL) to 38% (CH). This relatively small value reflects the good degradability and/or low toxicity of the compounds of the heat carrier fluid. Therefore, leakage, which would only minimally influence an assessment based on the standard weighting scheme, can be considered relatively uncritical even when extreme caution is needed in regard to local aquifer pollution.

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